

# Stratigraphic and palaeoenvironmental significance of a Pennsylvanian (Upper Carboniferous) palynoflora from the Piauí Formation, Parnaíba Basin, northeastern Brazil

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**Abstract.** A well-preserved palynoflora is reported from within a cored interval of a coal-exploratory borehole (1-UN-23-PI of the Geological Survey of Brazil) in the southern part of the Parnaíba Basin, northeastern Brazil. The sample studied is from the lower portion of the Piauí Formation. Its palynoflora is characterized by particular abundance of the trilete cavate/pseudosaccate miospores *Spelaeotriletes triangulus* Neves and Owens, 1966 and *S. arenaceus* Neves and Owens, 1966, together with cingulizionate forms mainly attributable to *Vallatisporites* Hacquebard, 1957 and *Cristatisporites* R. Potonié and Kremp emend. Butterworth *et al.*, 1964. Radially and bilaterally symmetrical monosaccate pollen grains are also well-represented, chiefly by *Plicatipollenites* Lele, 1964 and *Potoniopsisporites* Bhardwaj, 1954, respectively. Taeniate grains (i.e., monosaccates and bisaccates) are relatively minor constituents of the palynoflora; no marine microplankton were encountered. Several species are described in detail: the trilete apiculate spores *Brevitriletes levis* (Balme and Hennelly) Bharadwaj and Srivastava, 1969 and *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky and Gambero, 1979; and the taeniate pollen grains *Meristocarpus ostentus* sp. nov. and *Lahirites segmentatus* sp. nov. A Pennsylvanian (Late Carboniferous: late Westphalian) age is adduced for the palynoflora via its correlation with part of the Tapajós Group (specifically, the upper Itaituba Formation) of the Amazonas Basin in northern Brazil. The entirely land-derived palynomorphs, associated with abundant plant debris, corroborate previous suggestions that the lower part of the Piauí Formation accumulated in a nonmarine setting under conditions of aridity.

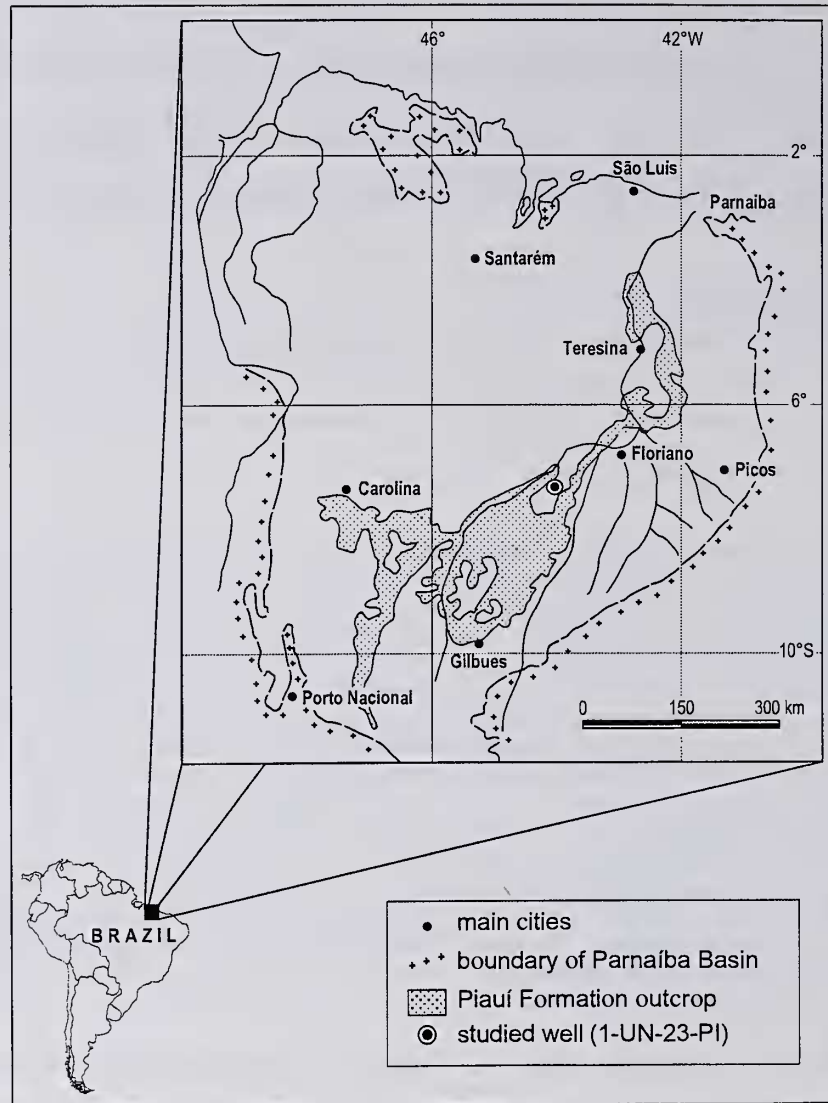
**Key words:** biostratigraphy, Brazil, Pennsylvanian, palynology, Parnaíba Basin, Piauí Formation

## Introduction

The Carboniferous-Permian rocks of the Palaeozoic basins in north and northeast Brazil provide excellent regional source and reservoir systems for liquid petroleum and gas. Palynology has been applied successfully as a basis for biostratigraphic subdivision of these upper Palaeozoic sequences, although the carbonate and evaporite intervals therein are normally only sparsely, if at all, palyniferous. In the Parnaíba Basin (Figure 1), the Balsas Group, with the Piauí Formation at its base, comprises these younger Palaeozoic deposits. During the Balsas tectonic-depositional cycle, the Parnaíba Basin experienced conditions of severe aridity, and received predominantly continental deposits (Cunha, 1986; Lima Filho, 1991). Lithologies are mainly of sandy, evaporitic, and muddy character and clearly reflect strongly oxidizing conditions of deposition.

Such factors obviously tend to militate against their palynostratigraphic potentialities. Accordingly, only a few palynological investigations have been conducted on upper Palaeozoic strata of the Parnaíba Basin. Inferences about age and palaeoenvironment (Müller, 1962) were based on material from exploratory wells drilled by Petrobras. At the beginning of the 1970s, the National Department of Mineral Production (DNPM) initiated research on coal encountered in several wells drilled close to the basin border, but no biostratigraphic analyses were undertaken. The present study concerns the lower part of the Balsas Group, viz., the Piauí Formation, as intersected in one of the DNPM wells. The aims are to determine the chronostratigraphic position of the strata, their possible correlation with other Brazilian Palaeozoic basins, and their environment of deposition.

The section of the 1-UN-23-PI well, investigated herein,



**Figure 1.** Locality map, Parnaíba Basin, northeastern Brazil, indicating site of borehole (1-UN-23-PI of the Geological Survey of Brazil) sampled for this study.

provides the first spore-pollen inventory for the lower part of the Piauí Formation. Obviously, a comprehensive palynological evaluation of the whole formation would necessarily be based on systematic sampling through the vertical extent of the formation, as developed in the subsurface and in outcrop.

As discussed subsequently, the identified spore-pollen assemblage can be compared, for purposes of stratal correlation, with those that characterize palynostratigraphic units established elsewhere; particularly the Upper Carboniferous-Permian palynozones defined in the Tapajós Group of the Amazonas Basin, northern Brazil (Playford and Dino, 2000b). Palaeoenvironmental implications of the Piauí palynoflora are somewhat limited, and are considered

in concert with physical evidence advanced by previous workers.

### Outline of stratigraphy

The Parnaíba Basin is essentially a Palaeozoic basin, but includes a cover of younger (Mesozoic and Cenozoic) strata. It is a substantial intracratonic entity, occupying some 600,000 km<sup>2</sup> in the western part of Brazil's northeastern region and positioned among fold belts that border the Guaporé, São Luiz, and San Francisco cratons. Total stratal thickness is *ca.* 3500 m, of which 2900 m comprise Palaeozoic sediments and the remainder are Mesozoic and Cenozoic deposits. The basin's Palaeozoic succession is divi-

sible into three major sedimentary cycles related to different tectonic, structural, and climatic circumstances. In ascending order, these cycles are manifested lithostratigraphically by what are termed the Serra Grande, Canindé, and Balsas Groups.

The initial cycle, of Silurian age, began with the tectonic-thermal development of a large depression in which fluvial, deltaic, and shallow marine sediments of the Serra Grande Group accumulated (Cunha, 1986; Góes and Feijó, 1994). With continuing tectonic evolution, the Canindé Group (of the second cycle) was deposited during Devonian-Early Carboniferous time. This consists of deltaic and shallow marine to paralic deposits at the base, grading upwards into fluvial-deltaics and periglacial, and culminating with fluvial-deltaic and storm-related deposits. The final (Balsas) Palaeozoic cycle in the basin commenced in the Pennsylvanian and extended through the Permian until earliest Triassic time. It followed pronounced uplift that exposed and eroded much of the Brazilian, indeed South American, platform. Accordingly, the Parnaíba Basin experienced strong erosion, as evidenced by its extensive and well-developed pre-Balsas unconformity. Moreover, the climate changed markedly: from the temperate and humid climates of the preceding cycles to conditions characterized by increasing heat and aridity (Mesner and Wooldridge, 1962, 1964). The sediments of this third phase signify dominantly continental conditions, with occasional marine incursions that became increasingly evaporitic.

### Piauí Formation

The term Piauí was introduced by Small (1914) to designate—as “Série Piauí”—the entire Palaeozoic section of the Parnaíba Basin. Its application was later restricted (Duarte, 1936) to constitute—as the Piauí Formation—the lowest of four formations that embody the basin’s youngest Palaeozoic sedimentary cycle (Balsas Group). This usage is still widely accepted and is adopted herein. The Piauí Formation is a predominantly clastic sedimentary unit, developed widely in the Parnaíba Basin and resting unconformably upon the Canindé Group. The formation crops out in a broad, almost continuous strip along the eastern and southern margins of the basin and discontinuously to the west (Andrade and Daemon, 1974; Suguio and Fulfaro, 1977). Its maximum thickness of *ca.* 350 m is encountered in the subsurface.

Mesner and Wooldridge (1964) proposed a twofold subdivision of the Piauí Formation. The lower part consists of pink to red sandstone; the upper part comprises alternating green and red shales, thin anhydrite beds, pink dolomite, and red or pale grey carbonate beds containing marine fossils. Lima Filho (1991), while maintaining the binary subdivision, modified slightly the Piauí Formation’s limits. He recognized several depositional systems in the forma-

tion, in particular citing evidence of aeolian and deltaic sedimentation and, towards the top, an episode of shallow marine, carbonate deposition. Accordingly, Lima Filho (1991) concluded that the Piauí Formation accumulated under arid conditions in a setting that included an extensive interior desert and an evaporitic marine basin.

The Piauí Formation consists chiefly of continental redbeds, aeolian sandstones, and fluvial deposits. However, brief marine incursions are attested by the presence of richly fossiliferous carbonate platform or lagoonal sediments, particularly in the formation’s upper part as developed in the basin’s northeastern sector. Known locally by such names as Mocambo, Contendas, Meruoca, Carimã, Vidalgo, and Boa Esperança, these marine strata become increasingly evaporitic upsection, providing evidence of progressive aridity. The marine faunas, though mostly undescribed, are diverse. They include bivalves, gastropods, cephalopods, brachiopods, trilobites, bryozoans, and echinoderms (crinoids especially), together with conodonts, agglutinated and calcareous Foraminifera, ostracodes, micro-molluscs, and other microfossils (see Duarte, 1936; Kegel, 1951; Kegel and Costa, 1951; Mesner and Wooldridge, 1964; Campanha and Rocha Campos, 1979; Assis, 1980). Faunal affinities between the Piauí Formation and the Itaituba Formation of the Amazonas Basin—as noted by such authors as Mendes (1966), Tengan *et al.* (1976), Campanha and Rocha Campos (1979), and Assis (1980)—support the hypothesis of a marine connection between the Parnaíba and Amazonas Basins during Pennsylvanian time.

### Material and methods

This study is based on material from a continuously cored well designated as 1-UN-23-PI and located in the state of Piauí, municipal district of Antonio Almeida, at latitude 7° 15′ 18″ South, longitude 44° 12′ 24″ West, in the southern Parnaíba Basin (Figure 1). Three samples were collected from the depth interval 137.6–145.8 m, representative of the top of the Piauí Formation’s lower portion (Figure 2). Of these samples, only one (a grey siltstone, at 145.0 m) proved palyniferous, yielding an abundant and well-preserved palynoflora. The two unproductive samples, collected at depths of 137.6 m and 145.8 m, are both greenish grey shales.

Conventional physico-chemical methods were applied in the laboratory preparation of the samples, specifically those outlined in Playford and Dino (2000a, p. 10–12). Light-microscope photographs of palynomorphs were taken with a Zeiss MC 80 DX camera coupled with a Zeiss Axioplan microscope using Kodak T-Max (100 ASA) film. Scanning electron microscopy assisted in the identification of several species.



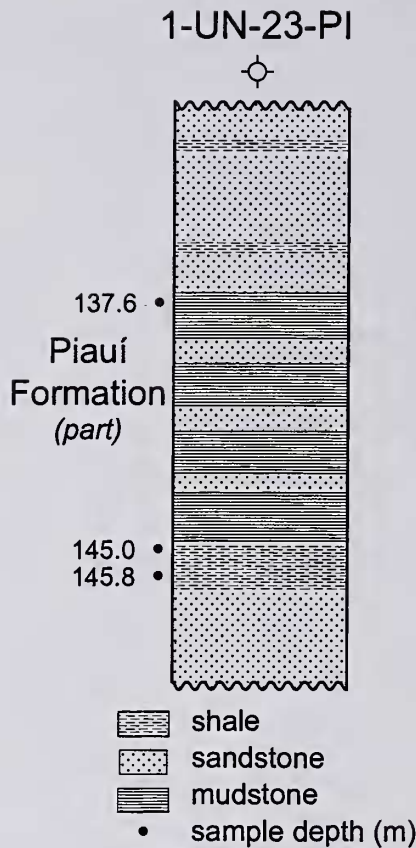


Figure 2. Portion of 1-UN-23-PI litholog showing palynologically sampled interval of Piauí Formation.

### Composition of palynoflora

The palynoflora recovered from the productive Piauí sample is dominated by pteridophytic trilete spores and gymnospermous monosaccate pollen grains occurring in almost equal proportions (each accounting for ca. 45% of the total assemblage). Taeniate bisaccate grains are relatively minor constituents (ca. 7%). In addition, fresh or brackish water green algae (*Botryococcus*, *Brazilea*) have been recovered. No palaeomicroplanktic elements were encountered.

Given below is an inventory of all palynomorph taxa identified. The large majority of these are illustrated by light micrographs (Figures 3, 5–8) and a few also by scanning electron micrographs (Figures 4, 9). In the system-

atic section, four species (asterisked hereunder) are described in detail, and brief notes are appended on discrimination of the two *Spelaeotriletes* species encountered. Illustrated specimens are listed in relevant figure captions with slide number followed by microscope-stage coordinates (per standard "England Finder" slide). Permanent repository of the specimens is Petrobras/Cenpes/Divex/Sebipe, Cidade Universitária, Quadra 7, Ilha do Fundão, 21949-900 Rio de Janeiro, RJ, Brazil.

### Spores

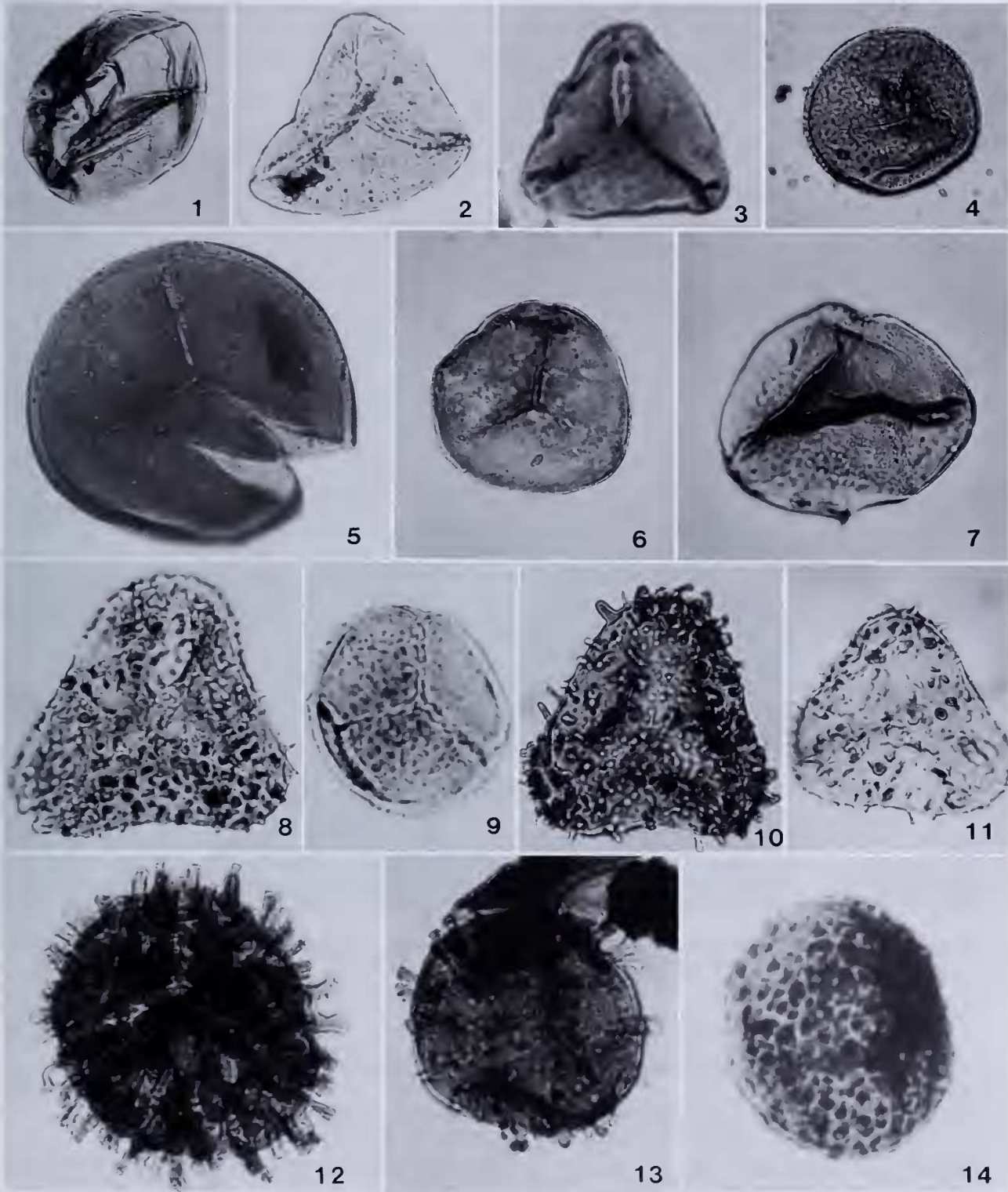
- Anteturma Proximegerminantes R. Potonié, 1970
- Turma Triletes Reinsch emend. Dettmann, 1963
- Suprasubturma Acavatitriletes Dettmann, 1963
- Subturma Azonotriletes Lubert emend. Dettmann, 1963
- Infraturma Laevigati Bennie and Kidston emend. R. Potonié, 1956
- Leiotriletes* sp. [Figure 3.7]
- Calamospora* sp. cf. *C. sinuosa* Leschik, 1955 [Figure 3.1]
- Punctatisporites gretensis* Balme and Hennelly, 1956 [Figure 3.5]
- Punctatisporites* sp. [Figure 3.6]
- Infraturma Apiculati Bennie and Kidston emend. R. Potonié, 1956
- Subinfraturma Granulati Dybová and Jachowicz, 1957
- Granulatisporites austroamericanus* Archangelsky and Gambero, 1979 [Figures 3.2, 3.3, 4.1]
- Cyclogranisporites minutus* Bhardwaj, 1957 [Figure 3.4]
- Subinfraturma Nodati Dybová and Jachowicz, 1957
- "*Acanthotriletes*" *menendezii* Gonzales-Amicon, 1973 [Figure 3.8]
- \* *Brevitriletes levis* (Balme and Hennelly) Bharadwaj and Srivastava, 1969 [Figure 3.9]
- Subinfraturma Baculati Dybová and Jachowicz, 1957
- Horriditriletes ramosus* (Balme and Hennelly) Bharadwaj and Salujha, 1964 [Figures 3.11, 4.2]
- \* *Horriditriletes uruguayensis* (Marques-Toigo) Archangelsky and Gambero, 1979 [Figures 3.10, 4.3, 4.4]
- Baculatisporites* sp.
- Raistrickia cephalata* Bharadwaj, Kar, and Navale, 1976 [Figures 3.12, 9.3]
- Raistrickia* sp. cf. *R. saetosa* (Loose) Schopf, Wilson, and Bentall, 1944 [Figure 3.13]
- Raistrickia* sp.
- Subinfraturma Verrucati Dybová and Jachowicz, 1957

→ Figure 3. 1. *Calamospora* sp. cf. *C. sinuosa*, ×500, 20005916E, K/42. 2, 3. *Granulatisporites austroamericanus*; 2, ×750, 20005916/3, Y45/2; 3, ×750, 20005916/3, R51. 4. *Cyclogranisporites minutus*, ×750, 20005916D, M36/3. 5. *Punctatisporites gretensis*, ×750, 20005916E, M49/2. 6. *Punctatisporites* sp., ×500, 20005916D, P55. 7. *Leiotriletes* sp., ×750, 20005916B, N39/2. 8. "*Acanthotriletes*" *menendezii*, ×1000, 20005916D, H39. 9. *Brevitriletes levis*, ×750, 20005916/1, A64/3. 10. *Horriditriletes uruguayensis*, ×1000, 20005916D, O38/1. 11. *Horriditriletes ramosus*, ×500, 20005916D, W48/3. 12. *Raistrickia cephalata*, ×750, 20005916E, V50/3. 13. *Raistrickia* sp. cf. *R. saetosa*, ×750, 20005916/1, B57. 14. *Verrucosiporites* sp. cf. *V. morulatus*, ×750, 20005916/2, U66.



*Verrucosisporites andersonii* Backhouse, 1988 [Figure 5.1, 5.2]  
*Verrucosisporites* sp. cf. *V. morulatus* (Knox) Smith and

Butterworth, 1967 [Figure 3.14]  
Suprasubturma Laminatitriletes Smith and Butterworth, 1967



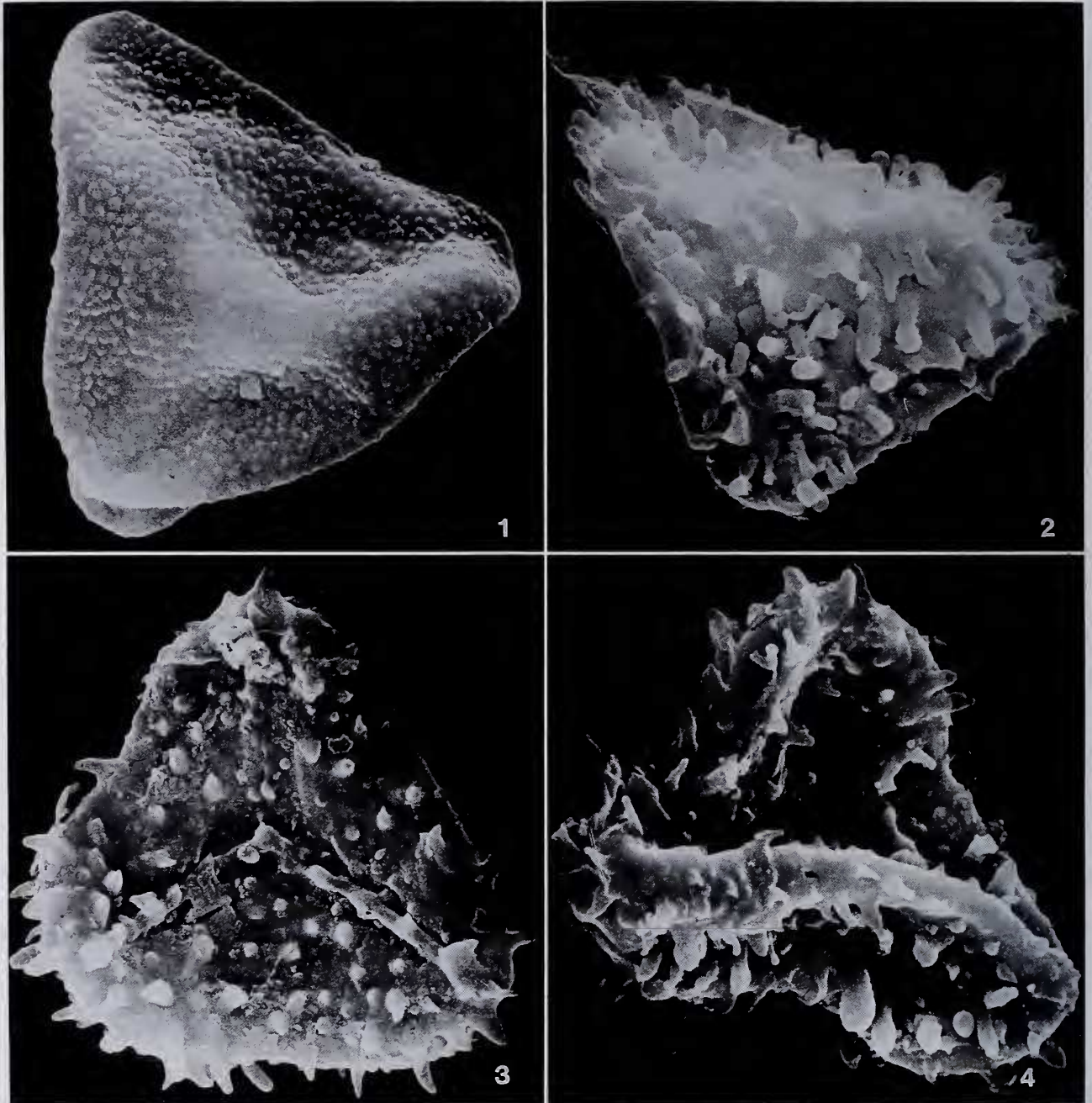


Figure 4. 1. *Granulatisporites austroamericanus*,  $\times 1900$ , 20005916/S1, S41/2. 2. *Horriditriteles ramosus*,  $\times 2000$ , 20005916/S1, S42. 3, 4. *Horriditriteles uruguayensis*, 3,  $\times 1900$ , 20005916/S1, Q41; 4,  $\times 2300$ , 20005916/S1, N39.

Subturma Zonolaminatitriteles Smith and Butterworth, 1967

Infraturma Cingulicavati Smith and Butterworth, 1967

*Vallatisporites arcuatus* (Marques-Toigo) Archangelsky and Gamarro, 1979 [Figure 5.3]

*Vallatisporites russoi* Archangelsky and Gamarro, 1979

[Figure 5.4]

*Vallatisporites* sp. 1 [Figure 5.5]

*Vallatisporites* sp. 2 [Figure 5.6]

*Vallatisporites* sp. 3 [Figure 5.7]

*Cristatisporites inconstans* Archangelsky and Gamarro, 1979 [Figure 5.10]



Suprasubturma Pseudosaccitriteles Richardson, 1965  
 Infraturma Monopseudosacciti Smith and Butterworth, 1967  
*Spelaeotriteles arenaceus* Neves and Owens, 1966 [Figure 5.9]  
*Spelaeotriteles triangulus* Neves and Owens, 1966 [Figure 5.8]  
 Turma Monoletes Ibrahim, 1933  
 Suprasubturma Acavatomonoletes Dettmann, 1963  
 Subturma Azonomonoletes Lubert, 1935  
 Infraturma Laevigatomonoleti Dybová and Jachowicz, 1957  
*Laevigatosporites vulgaris* (Ibrahim) Ibrahim, 1933 [Figure 5.11]  
 Infraturma Sculptatomonoleti Dybová and Jachowicz, 1957  
*Striatosporites heyleri* (Doubinger) emend. Playford and Dino, 2000a [Figure 5.12]

#### Pollen grains

Anteturma Variegerminantes R. Potonié, 1970  
 Turma Saccites Erdtman, 1947  
 Subturma Monosaccites Chitaley emend. R. Potonié and Kremp, 1954  
 Infraturma Aletesacciti Leschik, 1955  
*Florinites occultus* Habib, 1966 [Figure 6.10]  
*Florinites* sp. [Figure 5.13]  
 Infraturma Vesiculomonoraditi Pant, 1954  
*Potoneisporites brasiliensis* (Nahuys, Alpern, and Ybert) emend. Archangelsky and Gamero, 1979 [Figure 6.5]  
*Potoneisporites densus* Maheshwari, 1967 [Figure 6.11]  
*Potoneisporites elegans* (Wilson and Kosanke) Wilson and Venkatachala emend. Habib, 1966 [Figure 6.3]  
*Potoneisporites neglectus* Potonié and Lele, 1961  
*Potoneisporites novicus* Bharadwaj, 1954 [Figure 6.2]  
*Potoneisporites ovatus* (Kar) Gutiérrez, 1993 [Figure 6.9]  
*Potoneisporites simplex* Wilson, 1962 [Figure 6.1]  
*Potoneisporites triangulatus* Tiwari, 1965 [Figure 6.8]  
*Potoneisporites* sp. [Figure 7.4]  
*Peppersites ellipticus* Ravn, 1979 [Figure 6.7]  
*Caheniasaccites ovatus* Bose and Kar emend. Gutiérrez, 1993  
*Costatascyclus crenatus* Felix and Burbridge emend. Urban, 1971 [Figure 6.4]  
 Infraturma Triletesacciti Leschik 1955  
*Cannanoropollis densus* (Lele) Bose and Maheshwari, 1968 [Figure 7.5]  
*Cannanoropollis korbaensis* (Bharadwaj and Tiwari) Foster, 1975 [Figure 6.6]  
*Plicatipollenites gondwanensis* (Balme and Hennesly) Lele, 1964 [Figure 7.6]

*Plicatipollenites trigonalis* Lele, 1964  
 Infraturma Striasacciti Bharadwaj, 1962  
*Striomonosaccites ovatus* Bharadwaj, 1962 [Figures 7.9, 9.1]  
*Meristocarpus explicatus* Playford and Dino, 2000 [Figure 8.6]  
 \**Meristocarpus ostentus* sp. nov. [Figure 7.1–7.3]  
 Subturma Disaccites Cookson, 1947  
 Infraturma Disaccitriteleti Leschik, 1955  
*Linitisporites* sp.  
 Infraturma Striatiti Pant, 1954  
*Illinites unicus* Kosanke, 1950 [Figure 7.7]  
*Protohaploxylinus amplus* (Balme and Hennesly) Hart, 1964 [Figure 8.4]  
*Protohaploxylinus bharadwajii* Foster, 1979 [Figures 7.8, 8.3]  
*Protohaploxylinus* sp. cf. *Striatopodocarpites magnificus* Bharadwaj and Salujha, 1964 [Figure 8.5]  
*Striatopodocarpites* sp. cf. *S. phaleratus* (Balme and Hennesly) Hart, 1964 [Figure 7.10]  
*Striatoabieites* sp. cf. *S. anaverrucosus* Archangelsky and Gamero, 1979 [Figure 8.7]  
*Taeniaesporites* sp. [Figure 8.8]  
 \**Lahirites segmentatus* sp. nov. [Figures 8.1, 8.2, 9.2, 9.4]  
*Striatopodocarpites* sp. [Figure 8.9]  
 Turma Plicates Naumova emend. R. Potonié, 1960  
 Subturma Monocolpates Iversen and Troels-Smith, 1950  
*Cycadopites* sp.  
 Sculptured monocolpate form indet. [Figure 7.12]

#### Green algae (division Chlorophyta)

Class Chlorophyceae, order Chlorococcales  
*Botryococcus braunii* Kützing, 1849  
 Class Zygnemaphyceae  
*Brazilea scissa* (Balme and Hennesly) Foster, 1975 [Figure 7.11]

#### Systematic palaeontology

Genus *Brevitriteles* Bharadwaj and Srivastava, 1969

*Type species*.—*Brevitriteles communis* Bharadwaj and Srivastava, 1969; by original designation.

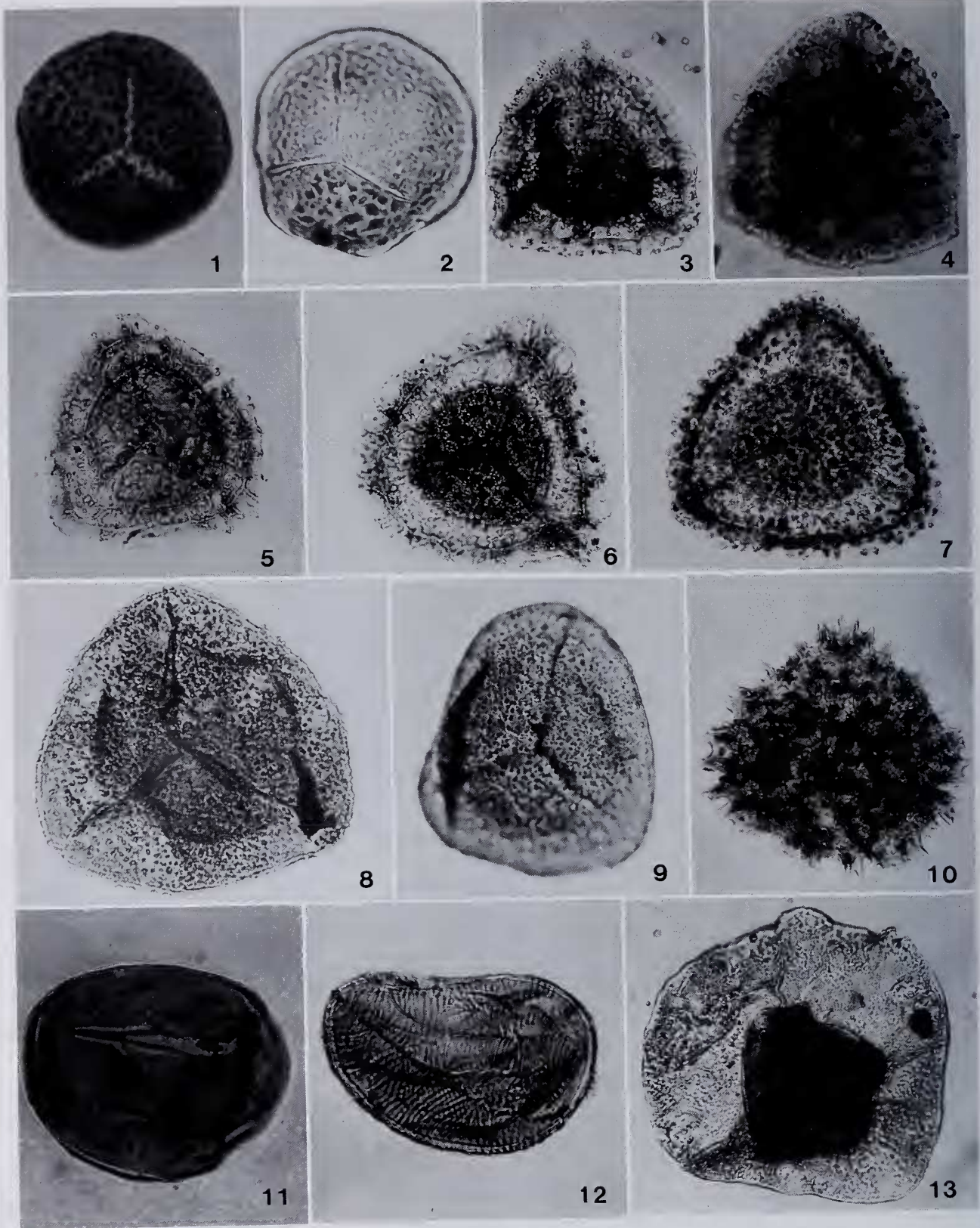
*Brevitriteles levis* (Balme and Hennesly)  
 Bharadwaj and Srivastava, 1969

Figure 3.9

*Apiculatisporites levis* Balme and Hennesly, 1956, p. 246–247, pl. 2, figs. 19–21.

*Brevitriteles levis* (Balme and Hennesly) Bharadwaj and Srivastava, 1969, p. 226–227, pl. 1, figs. 17–20.





*Anapiculatisporites ? variornatus* Menéndez and Azcuy, 1969, p. 88, 90; pl. 3, figs. A–H.

*Apiculiretusispora variornata* (Menéndez and Azcuy) Menéndez and Azcuy, 1971, p. 28.

*Retusotriletes baculiferus* Ybert, 1975, p. 186, pl. 1, figs. 21–23, non *Apiculatisporis* [sic] *levis* Balme and Hennelly; Césari, Archangelsky, and Seoane, 1995, p. 78; pl. 1, fig. 2.

For further synonymy see Foster (1979, p. 35).

**Description.**—Spores radial, trilete. Amb circular, sub-circular, or very broadly rounded subtriangular. Laesurae distinct, straight, extending almost to equatorial periphery; simple or accompanied by narrow and somewhat irregular lips; frequently terminating in  $\pm$  distinct curvaturae imperfectae. Exine 1.5–2  $\mu\text{m}$  thick, sculptured distally and equatorially with small, discrete, apiculate elements comprising spinae, coni, and galeae, 1.2–2.5  $\mu\text{m}$  long (usually ca. 1.5–2  $\mu\text{m}$ ), 0.5–2  $\mu\text{m}$  in basal diameter, spaced 0.5–2  $\mu\text{m}$  apart. Proximal surface laevigate or very sparsely and finely spinose/conate; sometimes polumbrate, with thickened (darkened) interradii emphasizing contact areas or parts thereof.

**Dimensions** (25 specimens).—Equatorial diameter, excluding sculptural projections, 22 (30) 37  $\mu\text{m}$ .

**Remarks and comparison.**—The specimens described above are in close accord with those described originally (Balme and Hennelly, 1956) and subsequently (Backhouse, 1991, 1993) from the Collie Coal Measures (Permian) of southwestern Australia, and also with Foster's (1979) material from Permian strata of the Bowen Basin, Queensland. In degraded specimens, the apiculate sculptural projections tend to exhibit decapitate or otherwise blunted termini and may thus resemble bacula. In terms of coarseness of sculpture, a morphological continuum exists among specimens belonging to *Brevitriletes levis* (Balme and Hennelly) Bharadwaj and Srivastava, 1969 (cf. Backhouse, 1991, p. 263).

Ybert's (1975) photomicrographs of his species *Retusotriletes baculiferus* leave no doubt as to its synonymy with *Brevitriletes levis*. The same is considered applicable to *Apiculiretusispora variornata* (Menéndez and Azcuy) Menéndez and Azcuy, 1971; see also Césari and Gutiérrez (2001, pl. 2, fig. 6). A specimen recorded by Césari *et al.* (1995, see above synonymy) as *Apiculatisporis* (sic) *levis* differs from the latter in having sparser, essentially rod-like sculpturing elements.

**Previous records.**—Known widely from the uppermost

Carboniferous and Permian of Gondwana. South American reports include those from Argentina (Menéndez and Azcuy, 1969, 1971; Mautino *et al.*, 1998; Vergel, 1998; Césari and Gutiérrez, 2001) and Brazil (Ybert, 1975; Burjack, 1978; Marques-Toigo, 1988).

Genus *Horriditriletes* Bharadwaj and Salujha, 1964

**Type species.**—*Horriditriletes curvibaculosus* Bharadwaj and Salujha, 1964; by original designation.

**Discussion.**—Foster (1979, p. 38) has clarified the diagnoses and differential diagnoses of *Horriditriletes* Bharadwaj and Salujha, 1964 and its type species.

*Horriditriletes uruguayensis* (Marques-Toigo)  
Archangelsky and Gamero, 1979

Figures 3.10, 4.3, 4.4

*Neoraistrickia uruguayensis* Marques-Toigo, 1974, p. 604, pl. 1, figs. 4, 5.

*Neoraistrickia baculicapillosa* Pons, 1976, p. 120–121, pl. 2, figs. 14–16.

*Horriditriletes uruguayensis* (Marques-Toigo) Archangelsky and Gamero, 1979, p. 424–426.

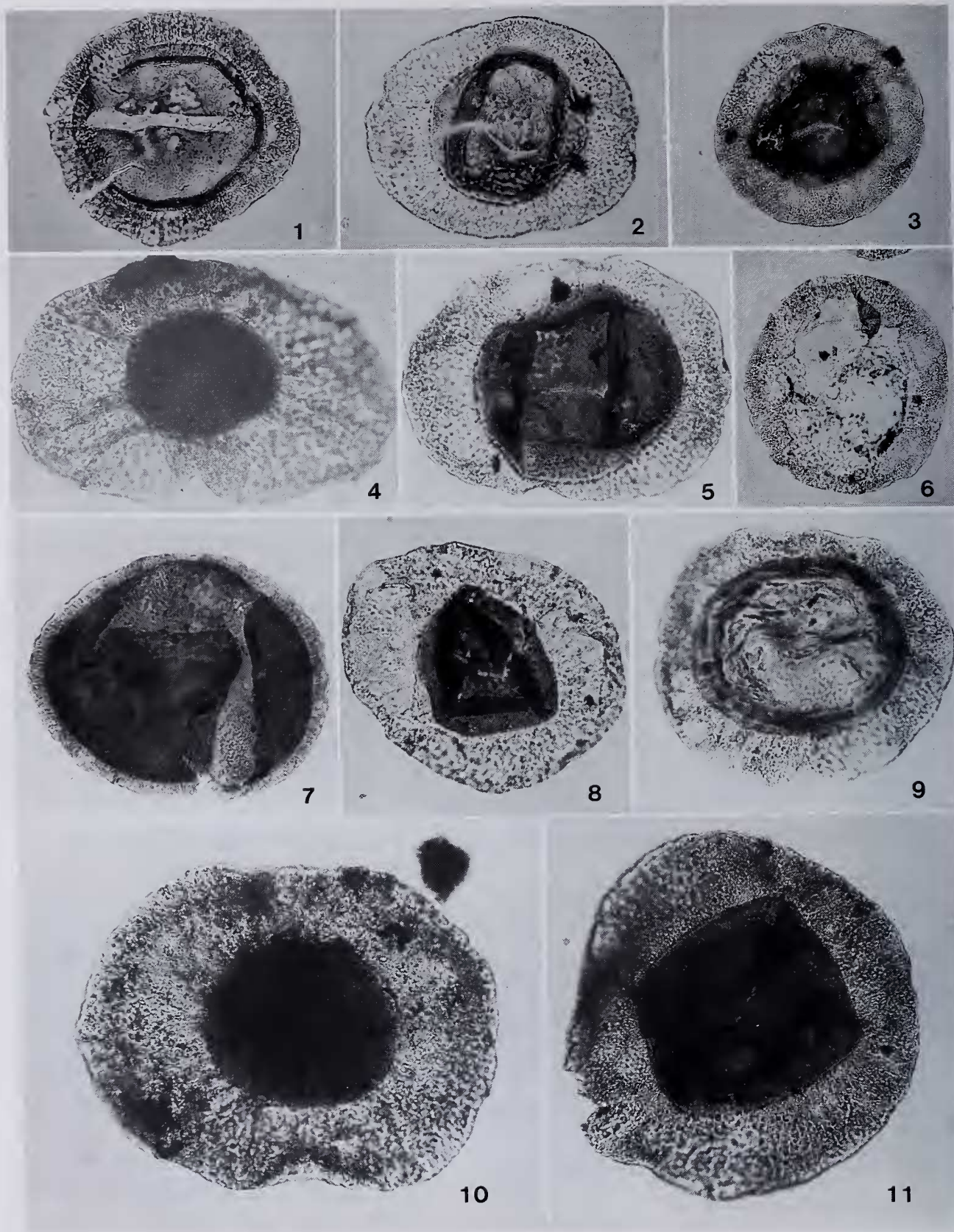
**Description.**—Spores radial, trilete. Amb subtriangular with straight or slightly concave sides and broadly rounded apices. Laesurae more or less distinct, straight, extending at least three-quarters of distance to equator, infrequently with narrow lip development. Exine 1–1.8  $\mu\text{m}$  thick, sculptured irregularly and heterogeneously with bacula (mainly), associated with verrucae, coni, spinae, and clavae of similar dimensions. Sculptural elements discrete and developed comprehensively, but more conspicuous distally and equatorially; length usually 1–4  $\mu\text{m}$ , bases 0.8–2.5  $\mu\text{m}$  in diameter and spaced 0.5–6  $\mu\text{m}$  apart.

**Dimensions** (20 specimens).—Equatorial diameter, excluding sculptural projections, 33 (43) 60  $\mu\text{m}$ .

**Comparison.**—*Horriditriletes uruguayensis* (Marques-Toigo) Archangelsky and Gamero, 1979 is distinguished from the type species (see Bharadwaj and Salujha, 1964, p. 193–194, pl. 2, figs. 34–39) by its larger size and more densely distributed sculpture; and from *H. ramosus* (Balme and Hennelly) Bharadwaj and Salujha, 1964, which has more uniformly baculate sculpture and subtriangular amb typically with slightly convex sides (Balme and Hennelly, 1956, p. 249, pl. 3, figs. 39–41).

◀ **Figure 5.** 1, 2. *Verrucosiporites andersonii*; 1,  $\times 750$ , 20005916/3, A49; 2,  $\times 750$ , 20005916/3, A47. 3. *Vallatisporites arcuatus*,  $\times 500$ , 20005916/3, D39. 4. *Vallatisporites russoi*,  $\times 750$ , 20005916/3, C54. 5. *Vallatisporites* sp. 1,  $\times 500$ , 20005916D, R39/3. 6. *Vallatisporites* sp. 2,  $\times 500$ , 20005916D, O36/4. 7. *Vallatisporites* sp. 3,  $\times 500$ , 20005916D, E50. 8. *Spelaeotriletes triangulus*,  $\times 750$ , 20005916D, F48/4. 9. *Spelaeotriletes arenaceus*,  $\times 750$ , 20005916D, O44. 10. *Cristatisporites inconstans*,  $\times 500$ , 20005916D, D48/4. 11. *Laevigatosporites vulgaris*,  $\times 750$ , 20005916E, H37/2. 12. *Striatosporites heyleri*,  $\times 500$ , 20005916D, S52. 13. *Florinites* sp.,  $\times 500$ , 20005916D, S57.







*Previous records.*—Originally described (Marques-Toigo, 1974) from the Lower Permian of Uruguay, *Horridiriletes uruguiensis* has been recorded subsequently in rocks of similar age from there and from Brazil and Argentina (e.g., Pons, 1976; Archangelsky and Gamarro, 1979; Marques-Toigo, 1988; Beri and Goso, 1996; Dias, 1994; Césari *et al.*, 1995; Beri and Aguilar, 1998; Vergel, 1998). According to Césari and Gutiérrez (2001), this species occurs in the Upper Carboniferous-Lower Permian interval of central western Argentina.

Genus *Spelaeotriletes* Neves and Owens, 1966

*Type species.*—*Spelaeotriletes triangulus* Neves and Owens, 1966: by original designation.

*Discussion.*—Playford *et al.* (2001) have provided a comprehensive review of *Spelaeotriletes* Neves and Owens, 1966 in terms of its diagnosis, differential diagnosis, and Gondwanan representation.

*Spelaeotriletes* is represented commonly in the Piauí palynoflora by two species that were instituted concurrently by Neves and Owens (1966) and share very similar morphological attributes; *viz.*, the type species *S. triangulus* (Figure 5.8) and *S. arenaceus* (Figure 5.9). Both species were described in detail by Playford and Dino (2000a, p. 21–22, pl. 5, figs. 1–7; pl. 6, figs. 5, 6) on the basis of numerous well-preserved specimens they encountered in the Pennsylvanian portion of the upper Palaeozoic Tapajós Group, Amazonas Basin. The difficulties that may arise in satisfactorily separating these species from each other have been discussed by Playford and Dino (2000a) and Playford *et al.* (2001); see also Spinner and Clayton (1973, p. 161), Playford and Powis (1979, p. 391), and Ravn and Fitzgerald (1982, p. 144). Pending re-examination of the respective type specimens of *S. triangulus* and *S. arenaceus*, and study of possible topotype material, the species are here distinguished - albeit somewhat provisionally as, for instance, in Playford *et al.* (2001)—in accordance with Neves and Owens's (1966, p. 345–346) original criteria (principally sculptural). These are that the exoexine (i.e., outside of the virtually laevigate contact faces) bears sculpturing elements that are generally coarser and more densely and regularly distributed in *S. triangulus* than in *S. arenaceus*.

*Previous records.*—*S. arenaceus* and *S. triangulus* have been reported widely, either individually or as a single merged specific entity, from upper Palaeozoic (more par-

ticularly, lower-middle Pennsylvanian) strata of both northern and southern hemispheres (Playford and Dino, 2000a, p. 21).

Genus *Meristocarpus* Playford and Dino, 2000b

*Type species.*—*Meristocarpus explicatus* Playford and Dino, 2000b; by original designation (monotypic).

*Meristocarpus ostentus* sp. nov.

Figure 7.1–7.3

*Meristocarpus* sp. C of Playford and Dino, 2000b, p. 100, pl. 4, figs. 1, 2.

*Diagnosis.*—Pollen grains bilateral, monosaccate, taeniate, monolete. Amb transversely oval to elongate, ends rounded. Laesura distinct to perceptible, straight or somewhat curved, length variable. Outline of corpus (in polar view) similar to amb, exine 1–1.5  $\mu\text{m}$  thick; proximal surface bearing 5–12 subparallel taeniae, mostly continuous, infrequently bifurcating, each 3–8  $\mu\text{m}$  wide, with intervening clefts 0.5–1.5  $\mu\text{m}$  wide. A pair of straight to broadly curved folds developed marginally across corpus and marking saccus attachments thereto. Saccus relatively narrow where adjoining transverse sides of corpus, with greatest development about longitudinal sides (“ends”) of corpus; fine to medium endoreticulum evident in well-preserved specimens.

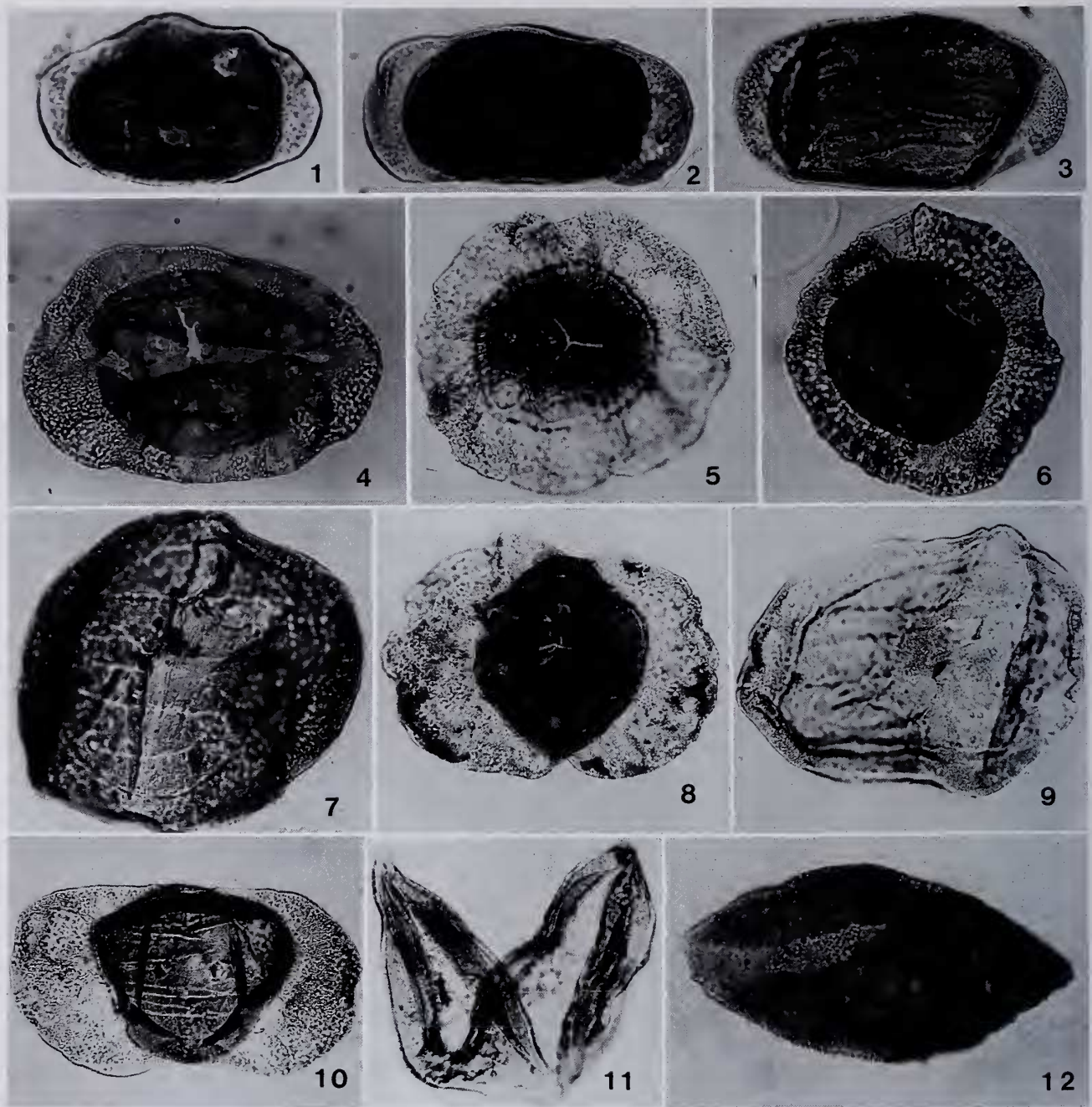
*Dimensions* (19 specimens, in polar aspect).—Overall breadth 82 (92) 110  $\mu\text{m}$ ; overall length 34 (48) 65  $\mu\text{m}$ . Corpus breadth 55 (70) 82  $\mu\text{m}$ ; corpus length 27 (43) 60  $\mu\text{m}$ .

*Holotype.*—Slide 20005916/3, S38/1; Figure 7.3. Proximal aspect. Amb transversely elongate-oval; overall length 47  $\mu\text{m}$ , width 88  $\mu\text{m}$ ; corpus well-defined, 43  $\mu\text{m}$  long, 72  $\mu\text{m}$  wide, outline closely conforming with amb, proximal face modified by 7 subparallel transverse taeniae extending for full corpus breadth, some bifurcation but mainly continuity; longitudinal corpus margins with prominent, straight to outwardly convex folds; maximum sacci development about corpus ends; sacci with fine endoreticulation; laesura perceptible, slightly curved, length 13  $\mu\text{m}$ .

*Type locality.*—Brazil, Parnaíba Basin, Piauí Formation; 1-UN-23-PI well, core, 145.0 m.

*Etymology.*—From the Latin, *ostentus*, stretched out.

◀ **Figure 6.** 1. *Potoneisporites simplex*,  $\times 500$ , 20005916C, P34/1. 2. *Potoneisporites novicus*,  $\times 500$ , 20005916C, G34/4. 3. *Potoneisporites elegans*,  $\times 500$ , 20005916C, D44/3. 4. *Costatascyclus crenatus*,  $\times 500$ , 20005916/3, T57/3. 5. *Potoneisporites brasiliensis*,  $\times 750$ , 20005916A, M37/4. 6. *Cannanoropollis korbaensis*,  $\times 500$ , 20005916C, D39/4. 7. *Peppersites ellipticus*,  $\times 500$ , 20005916C, A39/2. 8. *Potoneisporites triangulatus*,  $\times 500$ , 20005916C, J41/2. 9. *Potoneisporites ovatus*,  $\times 500$ , 20005916B, T41/4. 10. *Florinites occultus*,  $\times 500$ , 20005916/2, U66. 11. *Potoneisporites densus*,  $\times 500$ , 20005916/3, C48/4.



**Figure 7.** 1–3. *Meristocarpus ostentus* sp. nov.; 1,  $\times 750$ , 20005916/3, G50/3; 2,  $\times 500$ , 20005916B, O40/3; 3, holotype,  $\times 500$ , 20005916/3, S38/1. 4. *Potonieisporites* sp.,  $\times 500$ , 20005916D, G33/3. 5. *Cannanoropollis densus*,  $\times 500$ , 20005916D, M33. 6. *Plicatipollenites gondwanensis*,  $\times 500$ , 20005916F, P35/1. 7. *Illinites unicus*,  $\times 500$ , 20005916D,  $\times 50/3$ . 8. *Protohaploxylinus bharadwajii*,  $\times 500$ , 20005916/2, P57/3. 9. *Striomonosaccites ovatus*,  $\times 500$ , 20005916E, N/37. 10. *Striatopodocarpites* sp. cf. *S. phaleratus*,  $\times 500$ , 20005916C, F33/1. 11. *Brazilea scissa*,  $\times 750$ , 20005916/3, K46/2. 12. Sculptured monocolpate form indet.,  $\times 500$ , 20005916F, S44.

*Remarks.*—The identification herein of well-preserved specimens of this distinctive form, additional to those reported and designated informally by Playford and Dino

(2000b), enables its formal establishment as a new species. *Meristocarpus ostentus* sp. nov. is distinguished from other forms assigned to the genus mainly by the very prominent



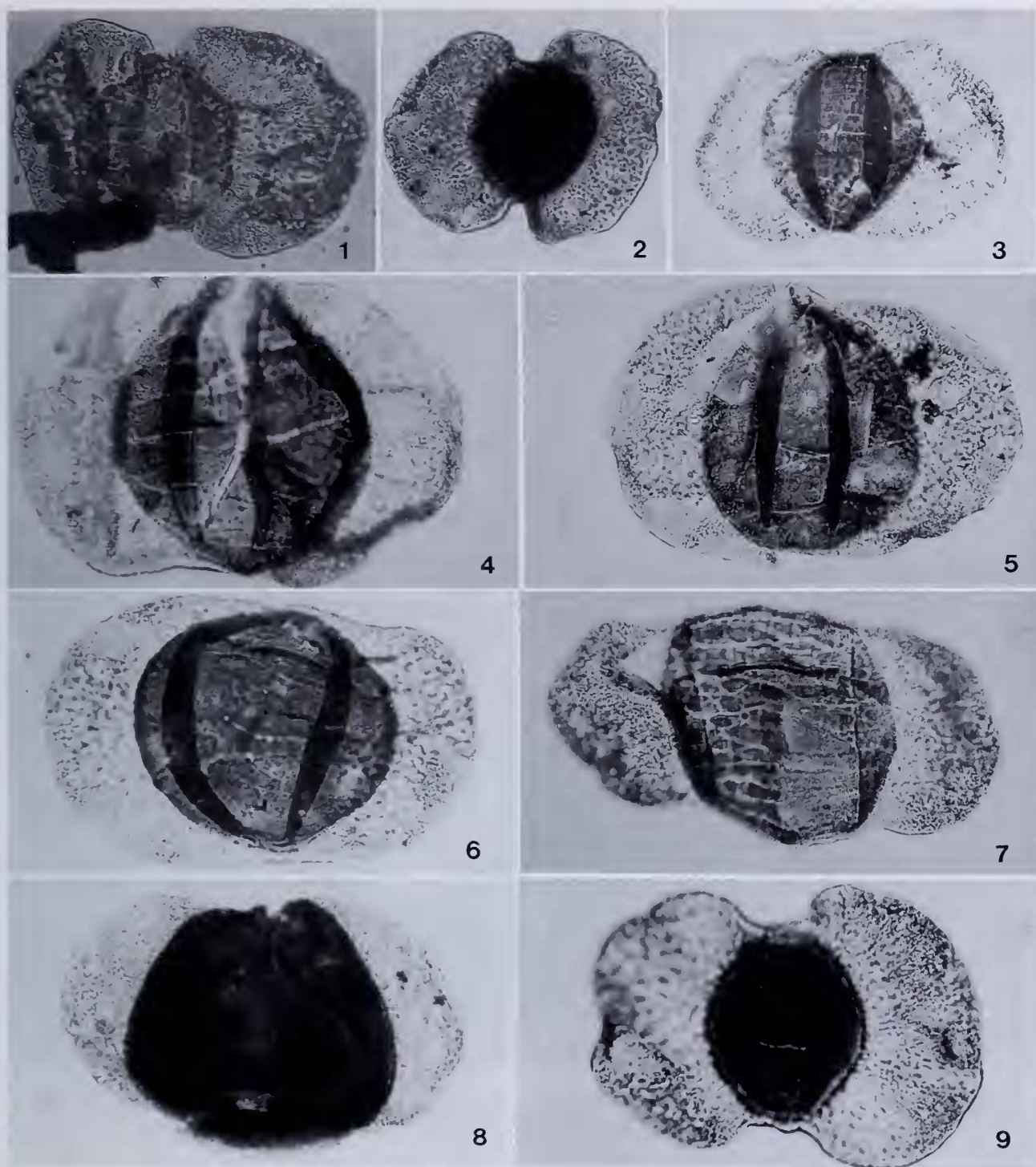


Figure 8. 1, 2. *Lahirites segmentatus* sp. nov.: 1, holotype,  $\times 750$ , 20005916A, M58/2; 2,  $\times 500$ , 20005916A, E39. 3. *Protohaploxypinus bharadwajii*,  $\times 500$ , 20005916F, D48/1. 4. *Protohaploxypinus amplus*,  $\times 750$ , 20005916/3, C48/2. 5. *Protohaploxypinus* sp. cf. *Striatopodocarpites magnificus*,  $\times 500$ , 20005916C, A39/4. 6. *Meristocarpus explicatus*,  $\times 500$ , 20005916A, N39/3. 7. *Striatoabietes* sp. cf. *S. anaverrucosus*,  $\times 500$ , 20005916C, D35/3. 8. *Taeniaesporites* sp.,  $\times 500$ , 20005916C, D34/4. 9. *Striatopodocarpites* sp.,  $\times 500$ , 20005916/3, D41/4.



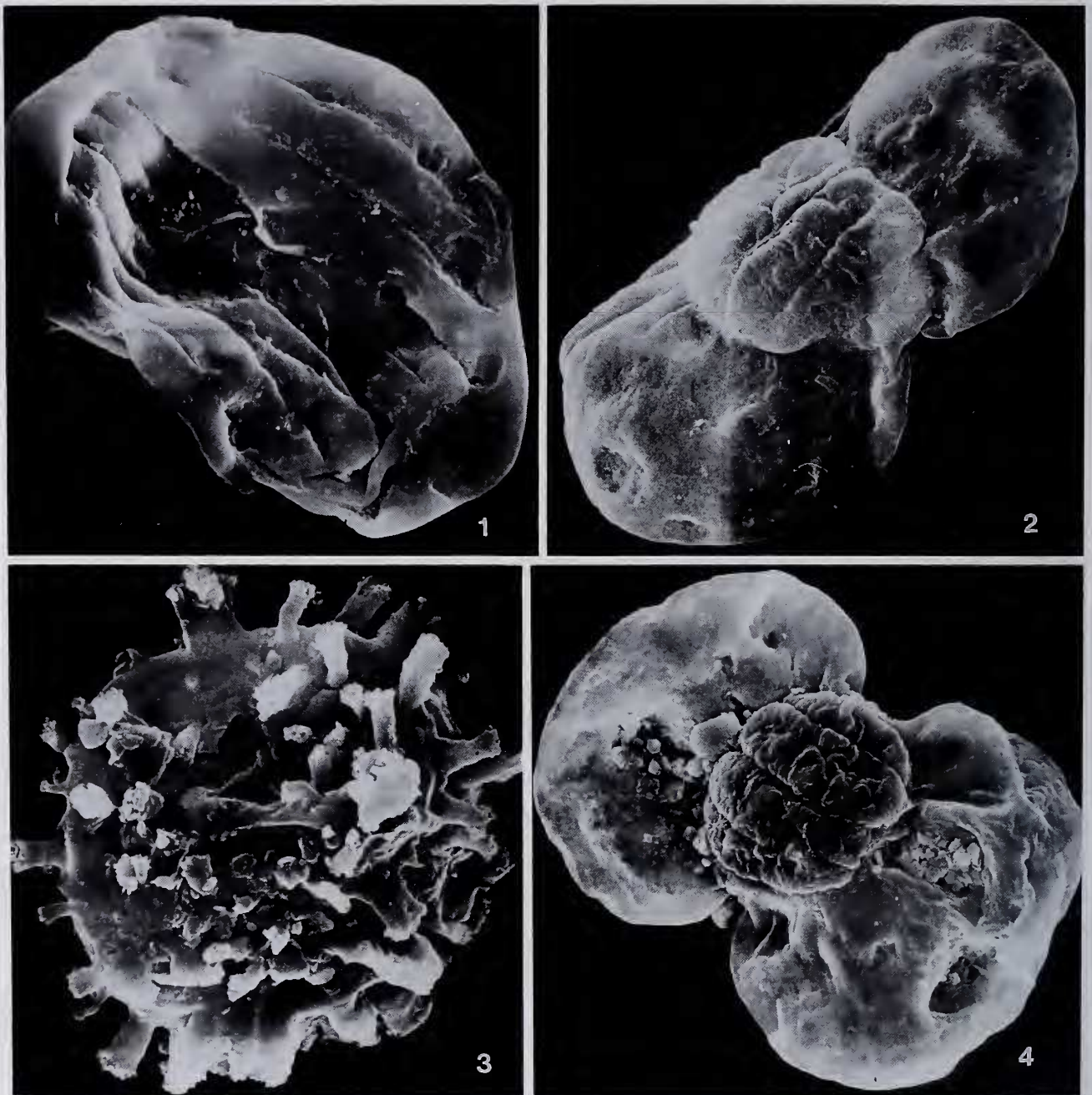


Figure 9. 1. *Striomonosaccites ovatus*,  $\times 1200$ , 20005916/S2, N39. 2, 4. *Lahirites segmentatus* sp. nov., 2,  $\times 800$ , 20005916/S2, N40/4; 4,  $\times 675$ , 20005916/S2, N55/4. 3. *Raistrickia cephalata*,  $\times 1500$ , 20005916/S2, P57/3.

elongation of its corpus and by relative proportions of the corpus and sacci.

*Previous records.*—From the Itaituba Formation, Amazonas Basin: *Illinites unicus* Zone, Westphalian C (Playford and Dino, 2000b).

#### Genus *Lahirites* Bharadwaj, 1962

*Type species.*—*Lahirites raniganjensis* Bharadwaj, 1962; by original designation (monotypic).

*Discussion.*—The salient attributes of *Lahirites* Bharadwaj, 1962, as exemplified by its type species, are circular

corpus bearing nine proximal transverse ("horizontal") taeniae that have a relatively coarse, segmented ("brickwork-like") appearance resulting from fine ("vertical"), linear, intra-taeniate channels cross-connecting the clefts bounding adjacent taeniae. The well-developed, protrusive sacci impart a distinctly diploxylonoid appearance. As discussed by Playford and Dino (2000b, p. 111), the three genera *Lahirites*, *Verticypollenites*, and *Hindipollenites*, as established by Bharadwaj (1962), have sufficient common features to render their mutual segregation problematical. Our choice of *Lahirites* as generic repository for the species newly described below is based mainly on its closer similarity to *L. raniganjensis* Bharadwaj, 1962 than to the type species of either of the other genera.

*Lahirites segmentatus* sp. nov.

Figures 8.1, 8.2, 9.2, 9.4

*Diagnosis.*—Pollen grains bisaccate, taeniate, strongly diploxylonoid. Corpus circular or near-circular with slight longitudinal elongation (polar orientation); exine 2–3  $\mu\text{m}$  thick, infragranulate. Cappa comprising 7–12 transverse taeniae that are continuous or, more commonly, irregularly furcant. Taeniae 7–10  $\mu\text{m}$  wide, separated by fine clefts 1–2  $\mu\text{m}$  wide; taeniae divided irregularly into broadly rectangular segments by fine channels disposed normally to inter-taeniate clefts, thus producing a brickwork-like negative reticulum. Cappula narrowly rectangular. Sacci > semicircular, with medium to coarse endoreticulum, distal attachment roots producing longitudinal folds near corpus borders.

*Dimensions* (16 specimens, in polar aspect).—Overall breadth 110 (135) 150  $\mu\text{m}$ ; overall length 63 (89) 105  $\mu\text{m}$ . Corpus breadth 35 (55) 65  $\mu\text{m}$ ; corpus length 50 (62) 75  $\mu\text{m}$ .

*Holotype.*—Slide 20005916A, M58/2; Figure 8.1. Proximal aspect. Strongly diploxylonoid; overall breadth 150  $\mu\text{m}$ , overall length 97  $\mu\text{m}$ ; corpus subcircular with slight longitudinal elongation (64  $\mu\text{m}$  x 75  $\mu\text{m}$ ), exine 2  $\mu\text{m}$  thick, featuring transverse, bifurcating taeniae, 7–10  $\mu\text{m}$  wide, separated by fine clefts and incised (approximately at right angles to the latter) by very narrow, irregular, and less distinct channels; cappula 23  $\mu\text{m}$  x 75  $\mu\text{m}$ ; sacci > semicircular, breadth 73  $\mu\text{m}$ , length 97  $\mu\text{m}$ , with medium-coarse endoreticulum.

*Type locality.*—Brazil, Parnaíba Basin, Piauí Formation; 1-UN-23-PI well, core, 145.0 m.

*Etymology.*—From the Latin, *segmentum*, partition, segment.

*Comparison.*—Certain Indian Permian species of *Lahirites* warrant comparison with *L. segmentatus* sp. nov. These species, with their principal morphological distinctions from *L. segmentatus*, are as follows: *L. raniganjensis*

Bharadwaj, 1962 (p. 92, pl. 13, fig. 172), taeniae non-furcant; *L. singularis* Bharadwaj and Salujha, 1964 (p. 204–205, pl. 8, figs. 119–121), generally smaller, corpus thin-walled but with distinct marginal ridge, non-furcant taeniae; and *L. rotundus* Bharadwaj and Salujha, 1964 (p. 205–206, pl. 8, fig. 125; pl. 9, figs. 126, 127), corpus with non-furcant taeniae and "laterally prominent marginal ridge".

### Correlation and age of palynoflora

Many of the palynomorphs in the present assemblage are identifiable with taxa that are known to have relatively broad stratigraphic ranges within the upper Palaeozoic of South America, and hence do not assist in definitive dating and correlation of the subject stratum. However, certain of the more vertically restricted species can usefully be applied biostratigraphically. These include the following: *Raistrickia cephalata*, *Vallatisporites arcuatus*, *Cristatisporites inconstans*, *Spelaotriletes arenaceus*, *S. triangulus*, *Striatosporites heyleri*, *Peppersites ellipticus*, *Illinites unicus*, and *Meristocorpus explicatus*. All have been documented previously from the upper Palaeozoic of Brazil (Amazonas Basin principally: Playford and Dino, 2000a, b) and/or of Argentina (e.g., Archangelsky and Gamero, 1979, Archangelsky *et al.*, 1996, Césari and Gutiérrez, 2001).

Müller's (1962) palynostratigraphic study included analysis of the Piauí Formation as cored in 15 oil exploration wells in the Parnaíba Basin (then termed Maranhão Basin). He recognized, in descending order, zones K, L, and M, covering the Piauí and the overlying Pedro de Fogo Formation and, supposedly (and, we believe, mistakenly), part of the underlying Poti Formation. The zones cannot be regarded, on present standards, as rigorously defined biostratigraphic units; they were ascribed generally to the Pennsylvanian (Westphalian-Stephanian). Zones L-M, represented by the Piauí Formation, include some forms encountered in the present sample; i.e., *Cristatisporites inconstans* (Müller's "Tl-2-I"), *Vallatisporites arcuatus* ("Tl-2-e"); *Verrucosiporites* sp. cf. *morulatus* ("Tl-r-b"), *Raistrickia cephalata* ("Raistr-a"), *Protohaploxypinus bharadwajii* ("V-D-i/st-a1"), and possibly *Spelaotriletes* sp. ("Tl-z-b"). Accordingly, the sample studied here is compatible with zones L-M (more particularly, the latter) of Müller (1962).

With regard to the Amazonas Basin, no really precise equivalence of the present assemblage can be established vis-à-vis the Playford and Dino (2000b) palynozonation of the upper Palaeozoic Tapajós Group. This may well be a consequence of the current study being based on only one, fortuitously productive sample from within an otherwise non-palyniferous Piauí interval. Moreover, very little is



known of the Parnaíba Basin's overall Carboniferous-Permian palynological sequence. Species considered to be stratigraphically significant in the Tapajós Group, and occurring also in the Piauí sample, include *Illinites unicus*, *Striatosporites heyleri*, and *Raistrickia cephalata*. Prima facie, therefore, the Piauí assemblage could be regarded as falling somewhere within the Amazonas zonal interval defined eponymously and collectively by these three species. However, viewed in more detail, it should be noted that both *S. heyleri* and *R. cephalata* are represented very sparingly, by only one or two specimens, in contrast to their respective zonal abundances in the Amazonas Basin. Correlation with the *Illinites unicus* Zone (Playford and Dino, 2000b, p. 120–121) appears most likely from the presence of *I. unicus* in association with *Meristocarpus explicatus* and *M. ostentus* and with plentiful *Spelaeotriletes triangulus*, *S. arenaceus*, and zonate-cingulizionate forms (*Vallatisporites*, *Cristatisporites*). Additional support for this zonal correlation is provided by the scant representation of taeniate bisaccate pollen grains (which become increasing prevalent in post-*I. unicus* palynozones).

The *Illinites unicus* Zone embraces the upper part of the Itaituba Formation, directly beneath the Nova Olinda Formation, in the Tapajós Group succession of the Amazonas Basin. Hence, zonal attribution of the study sample signifies correlation of at least the subject Piauí stratum with the upper Itaituba Formation. This effectively corroborates other palaeontological evidence (previously cited herein) of faunal affinities between the Itaituba and Piauí Formations, and strengthens the lithostratigraphic correlation between these two formations that was originally advanced by Mesner and Wooldridge (1964). It follows that the upper part of the lower Piauí Formation can be ascribed a mid Pennsylvanian (late Westphalian) age (Playford and Dino, 2000b, p. 131).

Correlation of the present Piauí sample with the Argentinian palynozonation cannot be effected in any satisfactory way owing to the very generalized characteristics promulgated for those zones (Césari and Gutiérrez, 2001, p. 133). The best that can be said is that the Piauí suite would be attributable to the zones DMb or DMc.

#### Palaeoenvironmental inferences

As discussed previously, sedimentological and palaeontological studies indicate an interplay of several environmental circumstances or settings nonmarine, paralic, marine, evaporitic during accumulation of the Piauí Formation. Many lines of evidence, including data from core descriptions, well logs, remote sensing, lithofacies analyses, and sedimentary petrography, point to the lower part of the formation being predominantly nonmarine and reflecting

conditions of aridity.

In the studied sample, the abundant land-derived plant debris in association with wholly terrestrial palynomorphs surely attest to nonmarine conditions. Moreover, the prevalence of monosaccate pollen grains, produced by cordaitalean gymnosperms, suggest arid climatic conditions. Regarding the green algal palynomorphs, the presence of *Botryococcus* permits no unequivocal palaeoenvironmental inferences (e.g., Batten and Grenfell, 1996, p. 210), other than indicating a quiescent aquatic situation; but *Brazilea* is suggestive of an exclusively freshwater habitat (Colbath and Grenfell, 1995).

#### Conclusions

1. The spore-pollen palynoflora recovered from the single productive sample, representing the upper part of the lower Piauí Formation in the southern Parnaíba Basin, comprises pteridophytic trilete spores associated with a range of gymnospermous pollen grains, principally monosaccates. Taeniate bisaccates are relatively uncommon.

2. In biostratigraphic terms, the assemblage bears closest similarity to the *Illinites unicus* palynozone of the Tapajós succession in the Amazonas Basin.

3. The zonal attribution connotes correlation of the palyniferous Piauí stratum with the upper part of the Itaituba Formation of the Tapajós Group, and dating of the stratum as mid Pennsylvanian (late Westphalian).

4. Such palaeoenvironmental indications that can be gleaned from the palynoflora corroborate the sedimentological, geophysical, and other prior data that imply a nonmarine depositional situation under arid conditions.

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